

Internet Photonic Sensing: Using the Internet Optical Transport Signals for Vibration and Deformation Sensing

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ABSTRACT

In this paper, we introduce *Internet Photonic Sensing* (IPS), a new framework for deformation and vibration measurement and monitoring based on signals that are available from standard fiber optic communication hardware deployed in the Internet. IPS is based on the hypothesis that atmospheric, seismic, anthropogenic and other natural activity cause deformations and vibrations in the earth that trigger detectable changes in standard optical signals that transmit data through Internet fiber. We assume a simple system component model for optical communication hardware and identify two candidate signals that may reflect deformation and vibrations and that can be measured through standard interfaces: Optical Signal Strength (OSS) and Bit Error Rate (BER). We investigate the efficacy of IPS through a series of controlled, laboratory experiments that consider how the candidate signals respond when fiber is subjected to a range of mechanical deformations. We believe that advancement of IPS offers the potential to transform the practice of scientific, commercial and public safety-related vibration monitoring applications by providing a highly-sensitive platform that is available at a global scale.

CCS CONCEPTS

• **Networks** → **Physical links**.

KEYWORDS

Fiber Optics, Ground Motion Sensing, Distributed Acoustic Sensing

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1 INTRODUCTION

The ability to accurately measure deformations and vibrations is central to a variety of public safety, scientific, and commercial applications including seismology, non-destructive evaluation, acoustic and flow monitoring, and security. Measuring displacements and

vibrations provides insights on issues related to failure, misalignments, utilization, wear and tear, flow rates, etc. and can be used for real-time alerting or post-facto assessment of system behaviors.

While the notion of monitoring the dynamic response of systems is intuitive, there can be significant challenges gathering measurements depending on the specific application. The key requirements for measuring mechanical responses include precision and accuracy of measurement, scale and range of sensors, time response, and deployability. Standard devices for measuring deformation and vibrations include laser displacement sensors, strain gauges, geophones, MEMS and piezoelectric accelerometers, gyroscopes, etc. Selecting a transducer depends on the requirements for deployment and sensitivity.

In this paper, we describe a new method for deformation and vibration measurement and monitoring that we call *Internet Photonic Sensing* (IPS). IPS is based on the observation that the behavior of light transmitted through optical fiber changes when the fiber is exposed to a broad range of deformations and vibrations. Our objective in this paper is to introduce IPS and to take initial steps toward demonstrating its efficacy by investigating how mechanical deformations on optical fiber that transmits Internet data can be identified in metrics that are widely available and easy to measure. To that end, we report results of a series of laboratory-based experiments that examine how stress on optical fiber affects two metrics available from standard Internet transport hardware. Our vision for IPS is highly sensitive, low-cost, world-wide deformation and vibration monitoring capability using already-deployed infrastructure. The efficacy of this vision is supported by recent reports of vibration monitoring using specialized equipment on deployed Internet fiber in [1, 16]

2 BACKGROUND

IPS is motivated by recent advances in (i) the use of fiber-optics for deformation sensing and (ii) the wide deployment of coherent optical systems in today's Internet. In this section, we provide a description of these technologies and the system component model that is a starting point for our work.

Fiber-optic deformation sensing. Fiber-optic sensing technology has been applied for over a decade to study deformation in buildings, dams, tunnels, and bridges for structural health monitoring (SHM) [9] and for studying natural earth processes such as earthquakes, landslides and glacier movement. Fiber-optic sensors have many benefits over other strain¹ sensors including sensitivity, stability, effective range and spatial resolution (i.e., the ability to identify strain location). Fiber-optic sensors can be divided into two categories: *Fiber Bragg Grating (FBG)* and *distributed systems*. A FBG sensor is a discrete device that is based on inscribing a pattern

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¹Strain ϵ is the dimensionless metric for deformation per unit length caused by a stress on a body.

in the core of single mode fiber that changes its refractive index. A FBG sensor identifies strain changes from the wavelength peak of the reflected light [13]. By increasing the acquisition rate, FBG sensors can be used to monitor dynamic responses.

Distributed systems utilize the interpretation of backscatter energy as an indication of strain. These systems are based on Brillouin Optical Time-Domain Reflectometry (BOTDR [17, 18]), or Coherent Optical Time-Domain Reflectometry (C-OTDR [2]). BOTDR is used in Distributed Strain Sensing (DSS) to sense strain and the C-OTDR is used in Distributed Acoustic Sensing (DAS) [6] to sense strain rates. The DSS sensitivity is on the order of microstrain over distances up to tens of kilometers with spatial resolution as fine as millimeters. DAS senses strain rates with sensing lengths of about 10 m, measurement separations of 1 m, and can be deployed over distances of tens of kilometers. The associated sampling frequencies for both techniques range from the order of seconds to milliseconds.

Coherent optics in the Internet. In the last ten years, physical layer networking hardware² has seen a significant shift to coherent optical communications equipment that employs a combination of modulation techniques to encode data in laser light, often at carrier wavelength of 1550 nm (193.5 THz). These systems rely on high-speed analog-to-digital converters that sample the received signal at a rate commensurate with the bandwidth of the optical channel, allowing the full characterization of the received optical signal. After conversion, a digital signal processor (DSP) is responsible for carrier frequency recovery, carrier phase recovery, channel equalization and down-sampling at the symbol rate.

The carrier phase and polarization provide direct paths to estimate cable deformations. Our challenge is that the DSPs in transport systems are designed to remove the variations in received light signals caused by vibrations, which are exactly the signals that we want to use in IPS. In a very real sense, this Internet signal garbage is distributed strain and vibration sensing gold.

System component model for transport hardware. We investigate the efficacy of IPS based on a simple component model for transport hardware. We assume that stresses and strains on optical fibers cause changes in transmitted light signals as they propagate through fiber [19]. While the optical signals such as carrier offset, relative phase, and the channel parameters are estimated by the DSP after A-to-D conversion, they are not typically available in higher level interfaces in commodity transport hardware. Thus, in this paper we consider how simple metrics that are readily available from transport hardware can reveal when fiber is subjected to deformations and vibrations. This approach enables experiments on commodity transport hardware and suggests the possibility of wide deployment of IPS if our hypothesis is correct.

We consider two signals in our study: Optical Signal Strength (OSS in units of dBm) and Bit Error Rate (BER - bit errors per second), which are commonly recorded in management information bases (MIBs) on transport hardware and are readily available for measurement via Simple Network Management Protocol (SNMP). These signals were selected based on our broad consideration of signals available in MIBs that might change when fiber is subjected to vibration stress. Other signals and combinations of signals will

be investigated in future work. OSS and BER have a straightforward relationship in an *additive white noise Gaussian noise* (AWGN) channel, which is a common starting assumption for noise analysis in a coherent optical channel. As the received OSS decreases, the signal-to-noise ratio (SNR) of the communications channel decreases proportionally. This decrease in OSS results in an increased BER. The BER of a Quadrature Phase Shift Keying (QPSK) communications signal (a modulation technique for encoding bits in coherent optical systems) in an AWGN channel can be derived from the SNR [15]: $BER = Q(\sqrt{2} \text{ SNR})$ where $Q(\cdot)$ is the q-function³. Similar expressions are available for higher order modulation schemes.

Related physical layer assessments. There have been several prior studies of optical signal characteristics measured on live fiber routes [3, 7, 19, 20]. These studies characterize signal perturbations due to environmental conditions, manufacturing defects and deployment issues. However, we are not aware of prior studies that use Internet signals to monitor displacements and vibrations. Monitoring signals in transport hardware for the purpose of network health assessment has also been the subject of several prior studies [8, 10]. These studies highlights the opportunities for insights from studying physical layer behavior. We take that one step further in proposing the opportunistic use of physical layer signals for vibration monitoring in IPS.

3 METHODOLOGY

To assess the efficacy of IPS we conducted a series of controlled, laboratory-based experiments using standard transport hardware to measure the cause-effect relationship between strain along a length of the optic fiber and our two candidate data transmission parameters: OSS and BER. The sending and receiving transport hardware consisted of transponders (Infinera AOLM-500-T4-1-C6) connected to Bandwidth Multiplexing Modules (BMMs) (Infinera BMM2-4-CX2-MS-A cards in separate DTC-A chassis), which are commonly found in the Internet infrastructure. The transceivers in these systems operate in the C-band (1550 nm) and were configured based on fiber lengths (thus OSS values for different lengths of fiber used in experiments will be different). During all of our experiments the transponders constantly send/receive streams of empty Optical Data Units (ODUs) at 100 Gbps (ODUs are normally populated with data from higher layers). The bit streams that make up the ODU are modulated via Dual Polarization-Quadrature Phase Shift Keying (DP-QPSK). The BMMs are connected via standard 9/125 single-mode fiber (9 and 125 are the diameters of the fiber's core and cladding respectively in micrometers).

We use three different configurations for our experiments: static bend tests through different bend radii on a 7 m segment of fiber, pull strain applied to a relatively short segment of fiber (1.5 m) and pull strain applied to a longer length of fiber (12.1 m) enabled through a system of pulleys. These configurations are depicted in Figure 2 in the appendix. Bending fiber is an extreme form of strain that degrades the signal by causing light to leak through the cladding [12]. The pull strain testing recognizes the relationship between strain and fiber length [11]: longer lengths of fiber may result in greater OSS and BER changes for the same level of strain.

²For the remainder of this paper we will refer to these as *transport systems* and *transport hardware*.

³The q-function can be expressed as $Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^\infty e^{-\frac{x^2}{2}} dx$.

For example, a displacement of 0.01 m causes a strain of 10^{-3} over a distance of 10 m and a strain of 10^{-6} over 10 km, assuming the potential signal loss mechanisms, yet the OSS and BER responses would be the same at both the higher and lower strains because the displacement and phase change are the same.

One of the main challenges in our work was to design a mechanical system to apply strains to an optical fiber. Ideally, the system would enable us to experiment over a range of strains levels that are consistent with the deformation and vibrations that occur in a range of 100s of nanostrains to microstrains, which is the target for standard deformation sensors ⁴.

We developed a test system that was able to subject fiber to tensile forces between 490 mN and 1.37 N. An illustration of our pull strain system is depicted in Figure 3 in the appendix. The 490 mN force subjects the fiber to about 100 microstrains ⁵. We argue that the ability to detect cause-effect at this level is indicative of the efficacy of IPS and establishes a critical starting point for future IPS experiments ⁶.

Our pull stress system attaches to the cable jacket near a 5 cm portion of exposed fiber via adhesive and using a S-hook attached to a load sensor, which in turn is connected to an Arduino-controlled servo motor (Atmega 328 board). A tensile deformation was applied to the fiber and the reaction force was measured with the HX711 Arduino-controlled load cell amplifier. The time series of the applied force was collected and transmitted using a Raspberry Pi 2 Model B Rev 1.1. Images of our lab setup for applying stress to fiber are shown in Figure 4 in the appendix.

SNMP is used to query the MIBs on the BMMs. Results of the SNMP queries were stored in files for post processing. The information maintained in the MIBs is structured in trees, with branches and end nodes referred to as *object identifiers* (OIDs). Some of OIDs we considered include the Number of Corrected Zeros, Number of Corrected Ones, Number of Corrected Bits, Number of Corrected Words, Q Factor, Pre Forward Error Correction (PreFEC), Bit Error Rates (BerPreFec), channel chromatic dispersion and channel Q value. We were able to query the receiving BMM for OSS and BER at an approximate (maximum) rate of 1 query per second. While this rate is sufficient for our experiments where stress is applied over tens of seconds to minutes, the SNMP query and MIB update rates are important factors for IPS. Ideally, rates should be at least 20 queries per second to sample a broader range of cultural and natural seismic signals.

4 RESULTS

Bend tests. Our first experiment examined the impact of a single bend strain on BER and OSS. We varied the radius of the bend, and separated bend and rest periods. Each bend strain period is 2 minutes. As shown in Figure 1 (top left), BER with 1 minute rest periods remains constant for bend radius of 3 cm and 2 cm indicating that the DSP and error correction can compensate for changes to light signal characteristics caused by stress in the fiber at

this level. However, when the bend radius reaches 1 cm BER jumps by two orders of magnitude indicating that the changes to light signal characteristics caused by stress in the fiber have resulted in significant degradation of the optical channel. Finally, the figure shows a complete loss of signal during the bend stress period with a radius of 0.5 cm. This indicates a complete loss of bits from the transmitted signal, thus no BER is measured during this period.

Figure 1 (bottom left) also shows that OSS degrades proportionally for all bend radii. In fact, OSS is sensitive to even light touching of the fiber when changing bend radius, which is why we show results with a 3 minute rest period. While the bend results clearly highlight the cause-effect of stress and the target signals, strains exerted at 1 cm and below are far beyond what would be exerted in the vibration monitoring scenarios that we envision for IPS.

Pull strain tests. We conducted pull strain tests using both short and long segments of fiber. We did not find significant differences in measured BER and OSS in the short vs. long fiber experiments, thus we only report the results of the experiments on long fiber segments in this paper. The focus of our experimental configurations was on (i) strain level, (ii) strain duration and (iii) rest duration between strain events. Our rationale for considering these aspects is based on our system component model. Namely, we want to understand how the target signals react to different stresses recognizing that the DSP is compensating for changes in the optical channel.

Figure 1 (left center) shows how BER and OSS react to different stress levels (load applied in increments of 89 mN from 490 nN to 1.37 N) where the duration of the stress and rest period between is constant at 5 min and 15 min respectively. The figure shows that under these stresses, BER is not obviously affected, but OSS is clearly affected even under the 490 mN load.

Figure 1 (right center) shows how BER and OSS react to 490 nN pull force over durations that vary between 10 sec and 50 sec at 10 sec increments with a rest period of 15 min. The figure shows that BER is inconclusive regardless of the duration of the stress. OSS is not affected by a stress applied for 10 sec, but is clearly reacting to stresses applied for longer durations.

Figure 1 (top and bottom right) shows how BER and OSS react to a 490 nN load applied over a duration of 15 min with rest periods that vary between 1 min, and 10 min. The figure shows that BER is inconclusive at this level of strain regardless of the duration of the rest period. OSS returns to the pre-strain levels for rest durations greater than 7 min. After reaching the maximum rest duration, recovery has to build up all over again.

5 DISCUSSION

Pull strain and bend testing. The pulley system in our laboratory tests has similarities to work by Henault *et al.* who conducted “pull-out” tests in which marks were placed 3.5 cm apart on 9 cm of bare fiber and the jacket of a 30 cm long sample [11]. As tensile force was applied, the separation increased linearly up to about 3.92 N. For higher loads, multiple shearing events occurred between the outer and inner layers because each concentric layer has different Young’s modulus. The behavior can be likened to “stick-slip” behavior in which minor strength variability between layers eventually leads to different portions of the glass/coating interface to slip. Differential displacement between the jacket and the inner 250-micrometer

⁴1 microstrain amounts 1 mm distance change between two points that are 1 km apart.

⁵Strain $\epsilon = (F/A)/E$, where F = tension force, A = cross sectional area of bare fiber for 250 micrometers diameter, and E is Young’s modulus of glass.

⁶Vibration tables with adjustable frequency and amplitude are commonly used to generate microstrains in fiber for lab-based testing. We will conduct experiments with vibration tables in future work.

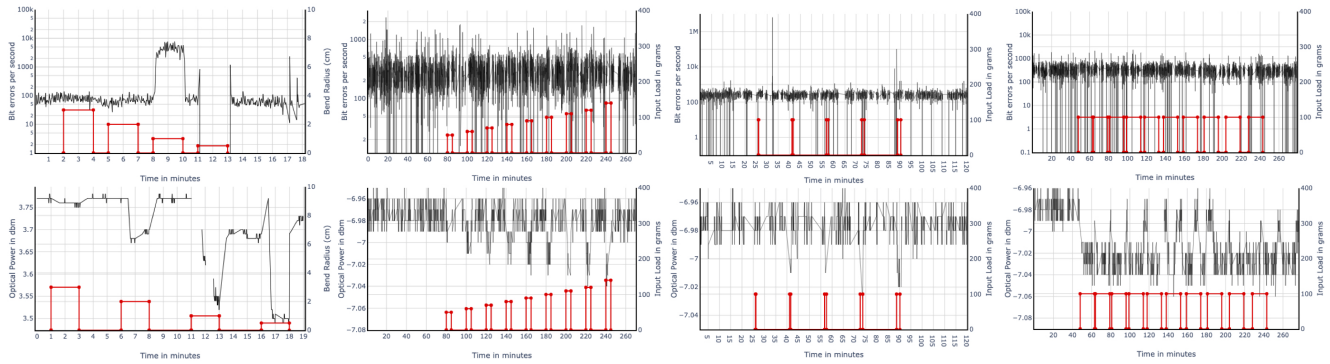


Figure 1: Results from lab experiments. In each case, BER (above) and OSS (below) and red bars show when stress was applied. **Left:** response to bend stress with radius of 3 cm, 2 cm, 1 cm and 0.5 cm each for a duration of 2 minutes, with rest periods of 1min. **Left center:** response to pull stress between 490 mN (50 g) and 1.37 N (140 g) (in 98 mN increments) on the long section of fiber. Load Period: 5 min, Rest period: 15 min. **Right center:** response for stress duration between 10 s and 50 s (in 10 s increments), on the long section of fiber. Load: 490 mN, Rest period: 15 min. **Right:** response for rest duration between 1 min and 10 min (in 1 min increments) on the long section of fiber. Load: 490 mN, Load Period: 15 min.

coating might produce small “microseisms” due to microcracking as illustrated in Figure 5 in the appendix. The acoustic emission noise could transiently increase BER.

Shearing between the primary coating and glass cladding during the IPS strain and bend tests similar to that observed by Henault *et al.* might be expected. The observed decrease in OSS is hypothesized to be caused by microbending effects of optical leakage or cable damage [12]. The attenuation coefficient increased approximately linearly for weights between 490 mN and 1.37 N. The signal strength recovered to its unweighted level, given a sufficient resting period. Full recovery required about 15 minutes; otherwise the recovery was incomplete. The load-recovery cycle became unclear after several cycles when a new recovery cycle began. The bend test showed no optical signal attenuation until the bend radius was reduced to a critical value of 0.5 cm.

Phase changes and strain. Our laboratory weight-and-bend tests showed high correlation with OSS but much less so with BER. We hypothesized that these results could be explained by relatively high shear stresses between the primary coating and the cladding, which created microbends and hence optical attenuation. We turn now to speculate how much smaller, elastic longitudinal strain might be observed using IPS.

The physics underlying this IPS application is that strain in optical fiber changes the index of refraction through the photoelastic effect. We first draw attention to how this basic principle presents similarities between IPS and DAS (we provide a more detailed compare and contrast of IPS vs. DAS in the appendix). DAS can detect changes on the order of 100 nanostrain over distances of a few meters. A DAS interrogator sends 1550 nm laser pulses separated by 100 microseconds and analyzes the Rayleigh backscattered light for the phase change of two locations a few meters apart (Δz). The change in strain ($\Delta \epsilon$) is $\Delta \epsilon = K \frac{\Delta \Phi}{\Delta z}$ where K is a constant that depends on the wavelength of the laser, the index of refraction, and the photoelastic constant [4].

This photoelastic proportionality applies to network data transmission. Even the same C-band laser frequency of 1550 nm is typical

for which $K = 100 \text{ n}\epsilon / \text{rad}$. The key conceptual link to IPS is to use BER during modulated coherent optical data transmission as a measure of phase change, $\Delta \Phi$, over a transmission distance, Δz , between transceivers. The photoelastic proportionality shows that the phase change over a path distance Δz is the product $\Delta \epsilon \Delta z$. We define a critical phase change, $\Delta \Phi_{crit}$, large enough to produce statistically measurable BER changes. In the case of QPSK, $\Delta \Phi_{crit} \approx \frac{\pi}{4}$. This condition is met easily as 100 nanostrain over 100 m (*i.e.*, the approximate separation between transceivers in an university campus network) gives a displacement of 100 nm and a phase change of 100 rad, requiring phase unwrapping (estimation of phase at a sufficiently high rate to unwrap the phase). DSPs in coherent optical receivers estimate, track, and correct the relative laser phase at rates on the order of microseconds. The phase estimates would be greatly beneficial to IPS and we expect they may be available in private interfaces on standard transport hardware. In this way, the DSP masks the vibration induced signals that would otherwise be more visible in BER and OSS signals studied herein.

Next steps. A number of possible future experiments are envisaged at the laboratory scale of meters to tens of meters, as well as in local and wide area networks. These include direct measurements of the relative carrier phase using a coherent optical modulation analyzer. Higher order modulation schemes, such as M-ary Phase Shift Keying techniques could be investigated. One would anticipate greater BER sensitivity to encoding methods that produce constellation points closely spaced in phase. Distinguishing between OSS and BER effects could be investigated by comparing 16-QAM with QPSK. Comparison of two-way data transmission over the same fiber link could serve to reduce spurious ISP interpretations. Our long-term goals are to (i) develop a vibration monitoring system based on an expanded set of received (post-DSP) signals with sensitivity that is sufficient for standard applications and (ii) establish the feasibility of using network data communication systems for ground motion monitoring in urban settings where transceivers are in close proximity. Our analysis shows this may be possible, and we expect that there are opportunities for further contributions.

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APPENDIX

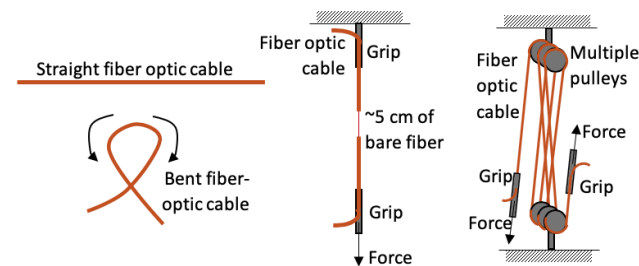


Figure 2: Mechanical deformation of the fiber: (left) bending, (center) pullout strain to a short section (1.5 m) of fiber, and (right) pullout strain to a long section (12.1 m) of fiber.

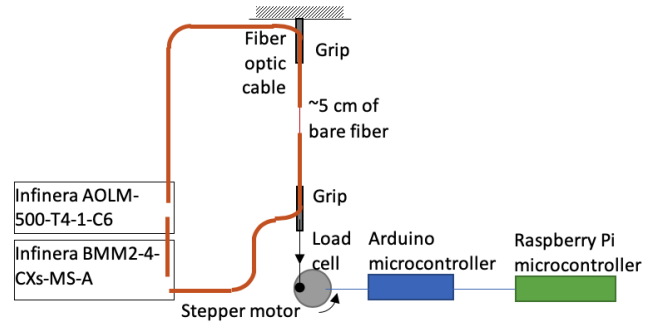


Figure 3: Test environment and electronic peripherals for generating pull strain, control and communication.

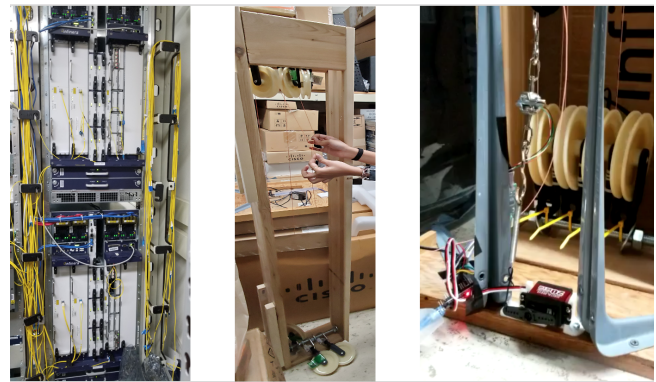


Figure 4: Lab setup for applying stress to optical fiber: (left) Infinera AOLM and BMM, (center) pulley system with fiber, and (right) Atmega servo motor and Arduino controller.

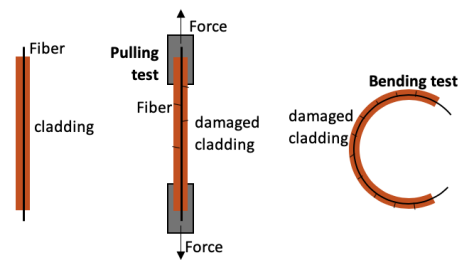


Figure 5: Potential damage mechanisms of the fiber and cladding.

IPS VS. DAS

The opportunity we are pursuing is to exploit the ubiquity and commodity nature of optical transceivers in the Internet (tens of millions) versus the limited and specialized nature of DAS interrogators (low one hundreds). The quantity difference is reflected in the price per unit, which differ by a factor of 20, for equivalent hardware and software. The starting point for both IPS and DAS is

injecting a coherent 1550 nm laser pulse into a span of fiber-optic cable. As illustrated in their respective schematics (e.g., [5, 14]), the phase of the output after passing through the sensing fiber is, in principle, obtainable at the output. In DAS, a length of reference fiber, on the order of 2 to 10 meters, is used for interferometry with the back-reflected signal from the sensing fiber under test. In IPS, the phase at the receiver is measured in relation to a local oscillator and synced to the transmitter. The basic physics of light traveling in fiber-optic cable mean that both DAS and IPS use the same photoelastic equation relating the phase change due to vibrational strain.

Although there are similarities in system components and operational principles for DAS and IPS, there are significant differences in operational details as well. (1) DAS uses the Rayleigh backscattered signal whereas IPS uses the forward transmitted pulse. DAS measures phase changes relative to a ten-meter reference fiber in every meter along the sensing fiber. This ten-meter sensing length is much better than the typical distance between transceivers in the Internet, which might be tens of meters but more likely 100's of meters even in dense network environments. In contemplating how IPS applications might be developed, the bi-directional data transmitted between two internet transceivers might make it possible to achieve higher spatial resolution. It might also be possible to modify internet transceivers to process the backscattered signal in a DAS-like mode, keeping in mind that the reflected power is smaller by several orders of magnitude. Because buried internet conduit bundles hundreds of fibers, stacking parallel data might be able to boost signal-to-noise significantly. (2) IPS is a spinoff from the main purpose of Internet communications, which is to recover error-free data for which phase errors are noise. The phase is important only insofar as it is true to the input and is not directly measured. In fact, transceiver DSPs are designed to reject phase variations, whatever the source. To the degree that ground vibrational signals are part of that noise, IPS characterization may be useful for data communication improvement in high-vibration environments such as urban corridors or perhaps large datacenters.

While our initial investigation has used OSS and BER to indicate vibration, other measures are under consideration for further study. For example, polarization would be independent of phase changes due to instabilities in laser frequency and could be a good indicator of vibration. Further, the MIB variables could be investigated as an IPS machine-learning problem. As we delve deeper, we hold the expectation that combinations of signals can be exploited more effectively in the future.

Finally, determining the location of an event is an important aspect of vibration monitoring, which will be addressed in future study. In areas of dense fiber deployment, localization will be possible by sensing signals on multiple links. In areas of sparse deployment, localization is more difficult. An ideal testbed for studying localization in IPS is the one used by Ajo-Franklin *et al.* in [1] that includes both operational fiber and DAS data as ground truth.

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